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POTENTIAL OF DIESEL ENGINES, FUELS AND LUBRICATION TECHNOLOGY

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FINAL REPORT

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16. Abstract

The chemical and physical properties of diesel fuel are reviewed along with their relationships to the fuel economy and emissions of diesel powered automobiles and light trucks. The fuels considered include both conventional and alternative diesel fuels. Additives are surveyed and their impacts on combustion and overall engine performance are discussed. The fuel economy potential of future lubricants is investigated, particularly (1) upgraded mineral oils, (2) synthetic oils, and (3) colloidal suspension in mineral oils.

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PREFACE

This report, DOT-TSC-NHTSA-79-42, is one of a series of four companion reports to DOT-TSC-NTSA-79-38 "Potential of Diesel Engine, 1979 Summary Source Document."* It reviews the chemical and physical properties of diesel fuel along with their relationships to the fuel economy and emissions of automobiles and light trucks. The fuel economy potential of future lubricants is also investigated. The author wishes to acknowledge the assistance of Dr. Thomas Trella of the Transportation Systems Center.

This report is a deliverable under PPA HS-027 "Support for Research and Analysis in Auto Fuel Economy and Related Areas."

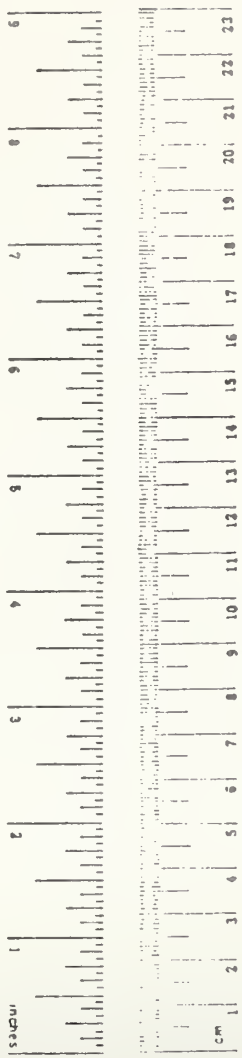
* "Potential of Diesel Engine, 1979 Summary Source Document," by T. Trella, Report No. DOT-TSC-NHTSA-79-38, March, 1980.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

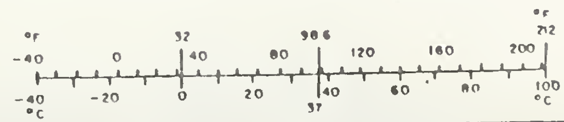
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. INTRODUCTION

The diesel engine's efficiency and performance have developed markedly over the past decade, while diesel fuel's features have remained unchanged or have even been impoverished. The only requirement diesel engine manufacturers have stipulated is that fuel features be as homegeneous as possible (i.e., Cetane Number, distillation interval) so as to leave main engine parameters, such as injection timing, unchanged. This essentially static condition of diesel fuel features could change dramatically in the future because of the following:

- The need for a diesel fuel that will reduce controlled and uncontrolled emissions, or will allow the use of antipollution devices to quarantee good fuel economy.
- The need to change the gasoline/diesel fuel ratio in favor of the latter to improve efficiency of crude oil refining.[1]
- The possibility of using alternative fuels (i.e., broad-cut, alcohols, vegetable oils derived from coal or other resources) in the coming years.

This report gives the main requirements of a diesel fuel suitable for diesel engines in passenger cars and light trucks. The fuels considered include both conventional and alternative diesel fuels.

The chemical and physical properties of diesel fuel are reviewed along with their relationships to fuel economy and emissions. Additives are surveyed and their impacts on combustion and overall engine performance are discussed. The fuel economy potential of future lubricants is investigated, particularly, (1) upgraded mineral oils, (2) synthetic oils, and (3) colloidal suspension in mineral oils.

2. REQUIREMENT/QUALITY

The ASTM standards D 975 related to fuels 1D and 2D describe distillate fuels for diesel engines, the former (type C-B) for city-bus and similar operation, the latter (type T-T) for diesel engines in trucks, tractors, and similar service (Table 2-1). The effects of fuel parameter variations on the performance of diesel engines are discussed below. The fuel parameters of interest here are viscosity, volatility, specific gravity, cetane number, pour point, sulphur content, and fuel composition. Viscosity can have a pronounced effect on the injection characteristics of distributor pumps which incorporate hydraulically-controlled governing and automatic timing advance mechanisms. The operation of these mechanisms, as well as full load fuel delivery, is affected so that low-viscosity fuels tend to give higher governed engine speed, reduced fuel delivery, and some delay in injection timing. These alterations could affect engine performance in terms of maximum rated speed, full load power output, exhaust emission and specific fuel consumption.

Lubrication of the fuel pump plungers within their barrels is provided by the fuel. Thus, if very low viscosity fuels are used for prolonged periods, wear may result. Undue wear is not likely unless fuel viscosity at 38°C is 1 centistoke or less. When fuel of sufficient viscosity is unavailable, a small quantity of lubricating oil, or anti-wear additive is normally added to prevent wear.

Fuel viscosity has little effect on the maximum droplet size within the fuel spray from the injector and little if any effect on spray tip penetration across the combustion chamber. However, viscosity does affect mean droplet size, such that low viscosity fuels produce a larger number of smaller drops, and hence give bushier sprays. This represents a way of reducing particulates in high-speed diesel engines, but experimental evidence in support of this hypothesis has not so far been obtained.

TABLE 2-1. ASTM STANDARDS D975

Test	ASTM D 975	
	1-D Fuel	2-D Fuel
Appearance	Clear and Bright	Clear and Bright
Distillation I.B.P.(°C)	166 - 199	171 - 210
10%	188 - 221	204 - 243
50%	210 - 249	243 - 282
90%	238 - 271	288 - 321
E P	260 - 293	304 - 349
Spec. Gravity (at 15.6°C) gm/cm^3	.826 - .806	.860 - .840
Total Sulphur % wt	.05 - .20	.2 - .5
Aromatics % vol.	8 - 15	27 min.
Olefins % vol.	Remainder	Remainder
Flash Point	48.9 C min.	54.4 C min.
Viscosity (at 37.8°C) CST	1.6 - 2.0	2.0 - 3.2
Centane Number	48 - 54	42 - 50
Conradson number on 10% residue (% wt max)	.15	.35
Water content % vol. max	trace	.05
Sediment % wt max	trace	.05
Ash % wt max	.01	.01
Pour point max	5.55 C°below	ambient
Copper corrosion max	3	3

— Volatility[2], understood as the initial boiling point, affects the quantity of fuel vaporized prior to the start of combustion. Consequent changes in premixing and preparation rates of combustible mixtures affect the NO_x level. Comparing two fuels with the same Cetane Number but with 30°C difference in initial boiling point, the 13-mode cycle NO_x levels were approximately 6 percent higher with the more volatile fuel.

The most significant fuel parameter[3] affecting hydrocarbon emission is the 50 percent recovered temperature. An increase in hydrocarbon emissions of up to 40 percent has been recorded when the 50 percent recovered temperature was changed from 316°C to 204°C. This may be due to the fact that decreasing volatility reduces the amount of fuel boil-off from the injectors during the exhaust stroke.

The combustion noise of I.D.I. diesel engines was reduced as much as three times when a fuel having a very low initial boiling point (about 50°C) was used.[4]

A reduction in odor with a decrease in volatility has been confirmed by many authors.[5] Fuel consumption decreases slightly when a high volatility fuel is employed. This point will be examined in greater detail in Section 2.2.

Finally, it is believed that volatile fuels such as kerosene produce less smoke than conventional diesel fuels. However, they also lower power output because they have a lower specific gravity.[6] Indeed, when measured at the same level of power output, the same amount of smoke was obtained. Particulate emissions decrease with a more volatile fuel.[7]

— Cetane number is known to affect ignition delay - i.e., the time interval between start of injection and start of combustion. The NO_x level is influenced by moderate changes in energy release rates or peak cycle temperature, which accompany changes in Cetane number. Up to 25 percent higher NO_x levels were found when switching from 47 to 33 cetane fuel.[9] Naturally aspirated diesel engines are more sensitive to fuel change than the turbocharged versions. In fact, because of higher pressure and

temperature at the end of the compression stroke, turbocharged diesel engines are less sensitive to the original ignition delay of the diesel fuel. At the same time, HC emissions increase 20 precent or more when using low Cetane fuels in D.I. diesel engines (Indirect Injection Diesel engines are less sensitive than Direct Injection Diesel engines) as many authors have noted.[9] This is due to the longer ignition delay that is similar to retarding the start of injection timing. Again, naturally aspirated diesel engines are more sensitive to low Cetane Fuels than turbocharged diesel engines.

Cold starting is especially important in automotive applications. When the engine is cold, heat transfer to the fuel is reduced and ignition delay periods are extended, partly because of lower cranking speed and partly because of lower compresssion temperature. Under these circumstances a high Cetane number is clearly beneficial.

White (cold) exhaust smoke resulting from incomplete fuel combustion is also typical of cold starts. The duration of cold smoke is reduced quite substantially by increasing the Cetane number and also by increasing the volatility (that is, by reducing the mid-boiling point) of fuel.

No great variations in combustion noise[10] or smoke from light-duty diesel engines were found as a consequence of changed Cetane number when fuel comparison was made at optimum static injection timing.

In terms of performance and consumption, light-duty diesel swirl chambers generally require more than Cetane 40 to avoid delayed combustion. Furthermore, for best fuel consumption and lowest emissions, Cetane number variations should range no more than six units.

– <u>Cloud point/pour point</u> influence the lowest temperature at which the fuel will give satisfactory performance. For the fuel supplier low temperature property controls can be very restrictive and most expensive. To meet a low cloud or pour point control

often involves a reduction in the distillation end point of the fuel, which in turn means a lower yield and greater difficulty in meeting specific gravity and Cetane Number requirements. The problem is wax precipitations in fuel lines and filters, causing blockage and fuel starvation.

The requirements of a fuel system suitable for operation at low temperatures are:

(1) Fuel tanks and fuel supply lines that are shielded from direct airflow. (2) Fuel supply lines of adequate dimensions and without sharp bends or unnecessary restrictions. (3) Coarse filters, which, if fitted at all, allow the passage of some waxy fuel and which are located in a position where they can take up heat rapidly from the engine. (4) Fine filters of adequate size and in a position where they can absorb heat reasonably quickly. (5) to Filter as little fuel as possible in excess of engine requirements, thereby reducing the rate of wax build-up in the fuel system components. If fuel systems were designed along these lines, then the fuel pourpoint, whether natural or depressed, would become the power limit of operation; refiners would enjoy greater freedom of component selection; and, vehicle users would rarely be embarrased by sudden spells of low ambient temperature.

Sulfur content influences (a) sulfur emission and (b) oxidation catalyst efficiency. Sulfur content of diesel fuel as given in EPA regulations (0.2 percent maximum for Grade 1 and 0.5 percent for Grade 2) is higher than for gasoline (0.1 percent). Diesel fuels, however, normally give 0.2 - 0.3 percent while gasoline is around 0.03 percent. A high sulfur content such as this means an SO_2 emission and maybe also SO_3 because of the presence of an oxidation catalyst.

No literature exists on the effect of these high levels of sulfur on the life of diesel oxidation catalysts. It appears that gas-solid equilibrium reactions are formed between SO_2 and the catalyst support, with the formation of aluminum sulfates. This problem is being studied now. Calcium and Magnesium sulfate

aerosols (at discharge), as well as other elements, derive from combustion reactions between SO_2 and additives or others from lubrication oil. Sulfur trapping systems have so far proven inefficient, because of an increase of the sulfur compounds formed which clog the collection system.

Fuel composition influences many factors of light-duty diesel engines. Combustion noise increases up to 1.5 times with a naphtenic fuel[10] in a swirl chamber diesel engine. It has been found that prechamber diesel engines like Mercedes are insensitive to fuel composition; i.e., combustion noise level is always low.

A recently-published paper[11] states that the mutagenicity of particulate emissions is influenced by fuel and to a lesser extent by the vehicle. Both the Benz (a) pyrene content and the mutagenic activity of emissions were the highest when the minimum quality fuel was used. This fuel has the lowest cetane value, highest aromatic content and highest nitrogen content of the five fuels examined. An increase of aromatic content can increase smoke and odors.[12] Recent tests carried out by G.M.[13] demonstrated that smoke and oxides of nitrogen increase when kerosene was used instead of Number 2 diesel fuel. However, particulate emissions were much lower (about 50 percent) with kerosene fuel. The differences are believed to be due to the combined effects of increased volatility and lower aromatics. The effect of aromatic content on particulate emission was thoroughly investigated in flame literature.[14]

2.1 ADDITIVES

Additives are used to modify certain physical or chemical characteristics of fuels. A list of the main types follows.

Anti-smoke: Organic salts, usually barium, have been examined in the past. They help in terms of any visibility measurement such as opacity measurement or the other smoke measurements, but they are useless in decreasing total particulates because barium and carbon particulates are obtained instead of carbon particles alone.[15]

Ignition improvers: Organic compounds, such as peroxides, nitrates or others have been examined. Particularly iso-propyl nitrate, iso-amyl nitrate and ciclohexyl nitrate have been studied. Unfortunately, these additives contain Nitrogen that can contribute to the formation of Nitrogen Oxides.

The effectiveness of ignition improvers varies greatly with fuel type and origin. It may increase the black smoking propensity of fuels to which they are added.

Fluidity/filterability improvers (pour point depressant): These are organic polymeric compounds. They change the growth habit of the n-paraffin wax crystals which are formed when diesel fuel is cooled below its cloud point temperature. The modified crystals are smaller and less cohesive. Consequently, they can flow more easily through the lines and filters in a fuel system.

When winterized fuel is not available kerosene can be added to diesel fuel to improve cold starts. When kerosene is difficult to find, regular gasoline can be mixed in with diesel fuel, up to 20 or 30 percent by volume. Because of the lower Cetane Number and the low relative density, normal engine output is reduced.

Anti-wear additives: These are organic materials intended to increase the lubrication quality of unusually thin distillate fuels which would otherwise cause accelerated wear of the mechanical, more heavily loaded components of the fuel system.

Injector lacquer detergents: These are organic compounds which keep the finely fitted surface in the fuel injector clean. Otherwise it can become coated with lacquer deposited by less thermally stable fuels.

Anti-rust additives: These mixtures of organic surfactant and dispersant compounds combat the corrosive effect of fuel contaminated with water. They passivate steel surfaces in the fuel system and also break water droplets into a fine dispersion which can be digested by the engine.

2.2 ALTERNATIVE FUELS

Many alternative fuels are now under consideration. They include, but are not limited to, distillates such as broad-cut and variable-composition fuels based on petroleum, coal, oil shale, biomass, etc., as well as transition fuels that lead to the above. Alcohols are also a major subject of interest. These include methanol, ethanol, higher alcohols, blends of these with hydrocarbons, etc. Vegetable oils like peanut or soybean oil can be very interesting for diesel application. Petroleum extenders are of interest, including emulsions of water and other materials with hydrocarbons, or alcohols. This report considers the implications of using alternative fuels to be developed for diesel engines in the future.

Broad-cut fuels

Several hypotheses have been proposed[16, 17] for maximizing engine efficiency with broad-cut fuels obtainable by simple crude distillation. The first[18] was to increase the Final Boiling Point of middle distillates from 360°C to 390°C. In this way approximately 10 percent more middle distillates are obtained and correspondingly less residual fuel oil. Such yield improvements have previously been limited by deterioration of the cold flow properties. With the introduction of filterability improvers it has been possible to produce middle distillates with a higher boiling point which possess good low temperature properties.

At the same time an attempt has been made to decrease the Initial Boiling Point. Diesel fuels having an Initial Boiling Point of about 50°C were examined.[19] More recently, broad-cut distillates with an End Boiling Point of up to 500°C were prepared. Tests on indirect injection diesel engines, swirl chamber and prechamber engines, are underway. The Cetane Number of these broad-cut fuels ranges from 40 to 50. These fuels may be regarded as having good characteristics, except for the cold flow properties. For example, the cloud point of the fuel previously mentioned is about 7°C and the pour point is +6°C. Flow improvers can improve it to some extent.

In the case of the fuel having a distillation range from 50°C to 400°C (Cetane Number = 49), some light duty diesel engine powered cars (Opel Rekord 1998, Mercedes 220) and an 8140 Fiat engine were examined. First tests showed no substantial differences in performances and smoke as the broad-cut fuel was used instead of a commercial diesel fuel (CN = 56.5). A slight decrease in fuel consumption was found when a fuel between 50 and 400°C was employed. Of course, the Static Injection Timing recommended by the manufacturer was advanced when the broad-cut fuel was used in order to take the longer ignition delay into account.

Coal derived Fuels

Fuels which now seem to make more economic as well as practical sense in the replacement of petroleum based gasoline and diesel fuel are fuels (gasoline and diesel fuels) and methanol derived from coal or from oil shale, or fuels from synthetic crude.[20, 21, 22, 23] Oil shale and coal are being considered for the production of synthetic crude. Lignites, sub-bituminous coals, can also be used.

Production of synthetic diesel fuel from coal was commercialized over 40 years ago in Germany.[24] Fisher and Tropsch studied the catalytic reduction of carbon monoxide to hydrocarbon liquids for years and in 1932 the first 1000 TPY plant became operational. By 1939, several plants were producing liquid fuels for the German war machine.

More recently, the South African company SASOL produced synthetic diesel fuel. SASOL's gasoil output (from Fischer Tropsch synthesis) is nowadays supplied as feedstock to an adjacent plant named Karbochem Pty, Ltd., which extracts olefins for its own use and returns the tailings to SASOL/NATREF. The latter stream is contaminated with varying amounts of benzene and chlorine so it cannot be added to the NATREF gasoil make. The material is consequently dumped into fuel oil.

In the early days of SASOL's operation, the gasoil output

was supplied to other oil companies (Shell/Mobil, etc.) and blended into distillate diesel fuel supplies marketed in the surrounding region. Supplies ceased around 1960. Main features of the fuel were as follows:

- Unusually high Cetane Number - around 70/75.
- Virtually sulfur free.
- Poor stability which led to the formation of lacquer deposits in injectors, stuck needles, etc.

Performance of this product was not entirely satisfactory in vehicles because of the high olefinic content which led to problems with injector fouling and needle lacquering in some engines. On the positive side, though, the feedstock value for chemical production from this material is extremely high due to the olefin content.

Gasoil marketed by SASOL currently is supplied by a local refinery which processes crude conventionally. In the future SASOL will produce gasoil from coal in a new plant coming onstream some time in 1982. This plant will employ hydrogenation to decrease unsaturation and the diesel fuel produce is expected to have Cetane Numbers in the range of 50 to 55. The product will be sulfur-free and should comply with accepted standards for high speed diesel fuels.

Alcohols

Methanol is the most promising alcohol from a global point of view because of the availability of coal or oil shares in many countries. In largely agricultural countries like India and Brazil ethanol is as strong a candidate as an alternative fuel. Alcohol has been studied extensively as a fuel for spark ignition engines.

Some studies were devoted to heavy-duty Direct Injection Diesel Engines.[24] The reason for the lack of studies in this field is that the very low ignition quality of alcohols makes alcohol unsuitable for diesel engines.

Two different patchs of inquiry were followed: additives to

increase the Cetane rating of alcohols, and forced ignition (dual fuel engine). In the case of methanol[24] a Swedish author, E. Holmer (by AB Volvo), concludes that a Cetane rating of 35 has been reached by using an additive (Cetanox) which is sufficient to run the tested engine with a compression ratio of 15:1 at an ambient temperature of 25°C. The amount of additive (20 percent) makes this solution uneconomical. A heat exchanger that uses engine coolant improves fuel economy. The influence of ambient temperature is eliminated, but there are considerable installation problems in a truck in service. Cold starts also cause problems. The other solution examined was the direct injection of methanol into the combustion chamber after diesel fuel. This prevents the methanol from cooling off the charge in the cylinder and thereby jeopardizing the diesel fuel ignition. This very peculiar type of dual-fuel operation was chosen to avoid spontaneous, uncontrolled ignition of methanol when carried in by induced air. Good performance and low smoke emissions, minimal HC emission and noise were attained. The design calls for a complete and separate diesel fuel system with tank, feed pump, injection pump and separate injectors. In any case, either because of economics (Cetane improver additive) or the extent of injection system modification (dual-fuel operation), these systems are unsuitable for installation of small diesel engines in passenger cars or light trucks.

Futhermore, another investigation[24] by Cummings and Seath concludes that the extent to which methanol could replace normal diesel fuel is limited by both quench and knock. Innovations such as mixture heating and ignition promoting additives allow greater substitution but result in unacceptable complexity of control in transient operation. The main conclusion is that alcohols can be used on a diesel running at constant speed. For this reason alcohols can not be employed on light-duty engines.

Vegetable oils

Peanut and Soybean oils appear to be more interesting than alcohols for use in diesel engines. Cold properties, such as

their pour point (between -1 and -5°C for peanut and less than -5°C for soybean), 8650 K Cal/Kg for peanut and 8420 K Cal/Kg for soybean oil, as well as high Cetane Number (estimated at over 50 in engine tests) make them interesting.

Peanuts come from the Arachis hypogea, an annual herbaceous plant cultivated in tropical countries. Oil content of peanuts ranges from 40 to 48 percent in weight. The 1975 world production of peanut oil was around 19.117 million tons, of which 11.128 came from India, the biggest producer; 40.4 to 63.4 percent (in weight) is trioleine ($C_{57}\ M_{104}\ O_6$), an oleic acid tri-ester (molecular weight 888.41). Trioleine is the main component of all vegetable oils except for palm oil.

Soybean oil comes from an annual herbaceous plant, cultivated in tropical and temperate-and-hot climates. It originates from the Far East. Oil content varies from 10 to 15 percent. The 1975 annual production was estimated at 68.356 million tons. Production is on the increase, especially in Brazil. Soybean oil's pour point can be very low: (between 10 and -15°C) because of its high saturation point (132 - 139 iodine number) and lower viscosity than peanut oil (8 to 9 Engler). Its high saturation index shows lower ignition delay, which translated into a much higher Cetane Number than peanut oil. At the same time it shows a possible tendency to produce lacquer deposits, as already observed for diesel fuels derived from coal. This must be proven after duration tests.

The Fiat Research Center, sponsored by the Industrial Vehicles Corporation (IVECO), has tested peanut and soybean oils, either by themselves or mixed with commercial diesel fuel (30/70 percent) on a 4-cylinder in-line 3.5 liter displacement direct injection diesel engine. Tests were completed by tracing an injection timing curve delayed with respect to the one for diesel fuel because of the higher Cetane Number of vegetable oil. The delay is particularly high for soybean oil (3° CA DTDC from 1000 to 2400 rpm, 6° CA BTDC at 2400 rpm and 10° CA BTDC from 2400 to 3200 rpm as compared with 14° CA BTCD of Static Injection Timing recommended

by the Manufacturer). With a fuel consumption that gives equal power, a slight thermal efficiency increase and a 20 percent NO_x decrease were observed when passing from diesel fuel to vegetable oil. Furthermore, a marked reduction of combustion noise and less objectionable odor were observed as compared with diesel fuel.

Water diesel oil emulsion

Emulsion of water in diesel fuels (as much as 20 percent by volume) with surfactant may be a solution to reduce both the NO_x and particulates. In fact, the high heat of vaporization of water favors temperature decrease on the one hand (lower NO_x level) and greater spray bucking on the other (closer to a homogeneous mixture). Work is under way at Princeton University (Prof. I. Glasmann). Some industrial laboratories (such as Lucas) are also conducting tests along these lines. By employing water-in-oil emulsions with surfactant a reduction of particulate emissions from 10-20 percent was found.[25]

3. LUBRICATION

3.1 INTRODUCTION

No distictions have been made in this report between lubricants for use in diesel engines and those for use in spark ignition engines for two basic reasons:

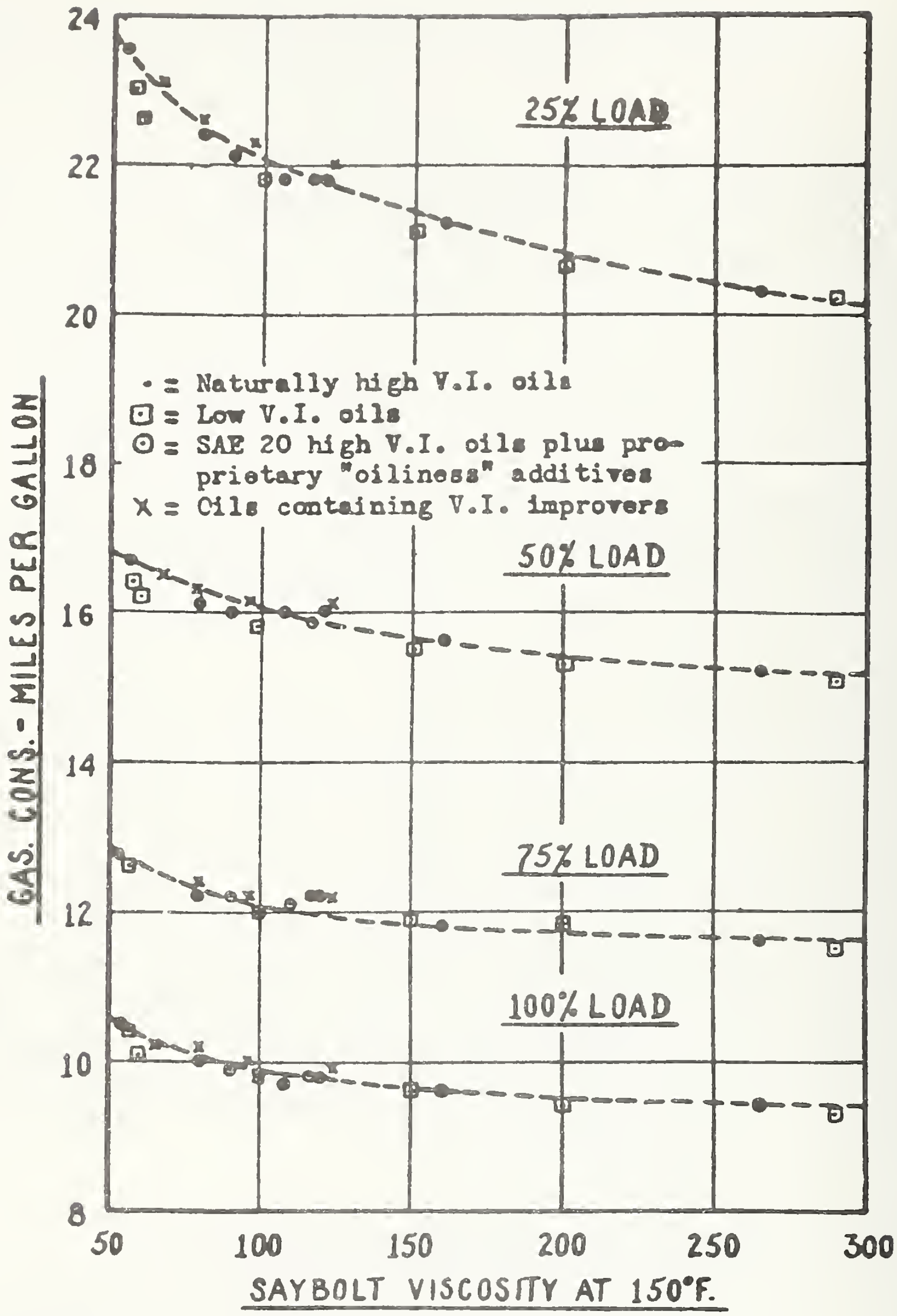
- European manufacturers of high speed diesel engines for cars have not yet come to common decision on the type of lubricant to adopt for these engines. At present, engine oils are employed according to Military specification MIL-L-2104C, MIL-L-46152 or MIL-L-2104 B, depending on the distictive features of the different engines to be lubricated and on the oil drain period recommended.
- The qualitative level of the oil (MIL-L-2104C, MIL-L-46152, MIL-L-2104B, etc.) has no significant influence on the parameters directly related to fuel economy.

From the viewpoint of fuel economy, the upgrading of conventional mineral oils is attainable through the reduction of the "true" viscosity of present engine oils by employing either multigraded oils or single grade oils of lower viscosity (provided they are formulated so that they do not give rise to disadvantages, such as wear problems). Therefore, the relationship between fuel consumption and engine oil viscosity has been taken into account.

Again, as to fuel economy, the employment of soluble friction modifier additives seems very promising. Unfortunately, at present, no reliable information on the evaluation of these additives is available.

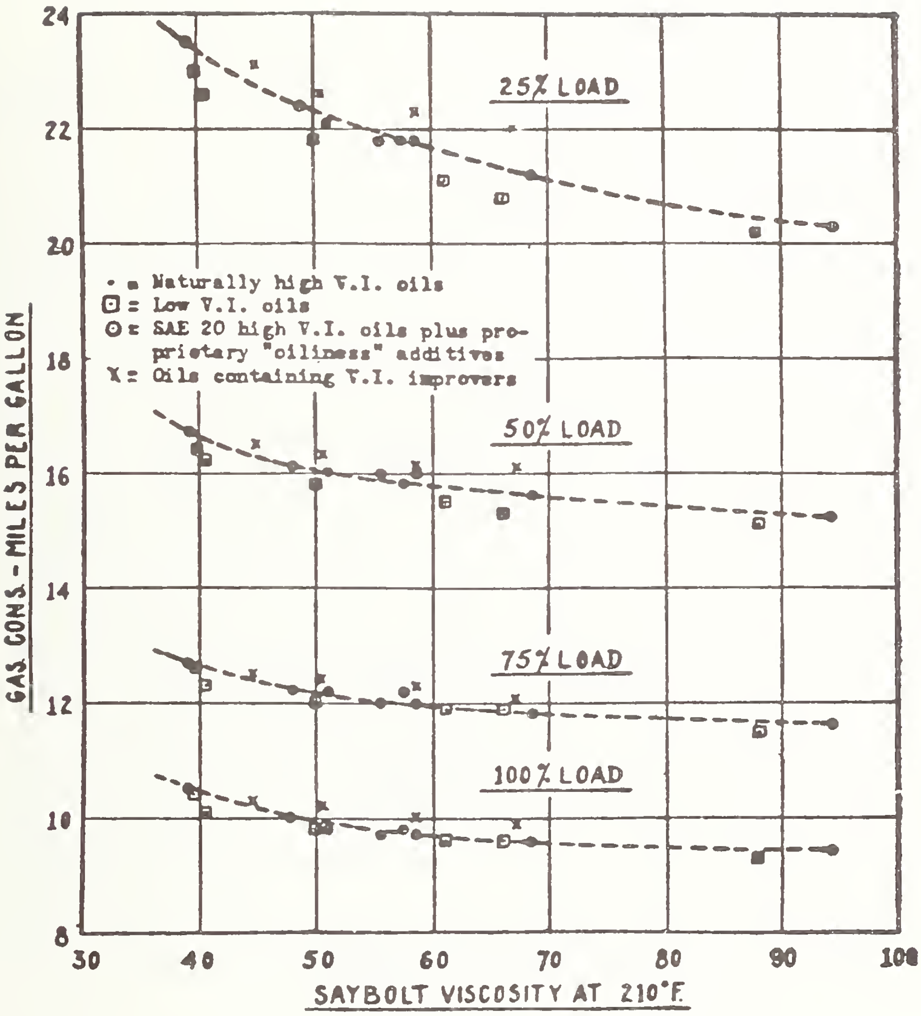
3.2 FUEL ECONOMY WITH UPGRADED MINERAL OILS

In 1954 Georgi showed the relationship existing between engine oil viscosity and fuel consumption at different engine loads (25, 50, 75, 100% load). Typical results are shown in Figures 3-1, 3-2, and 3-3. The data obtained in the form of fuel consumption ratios as related to oil viscosity grade are



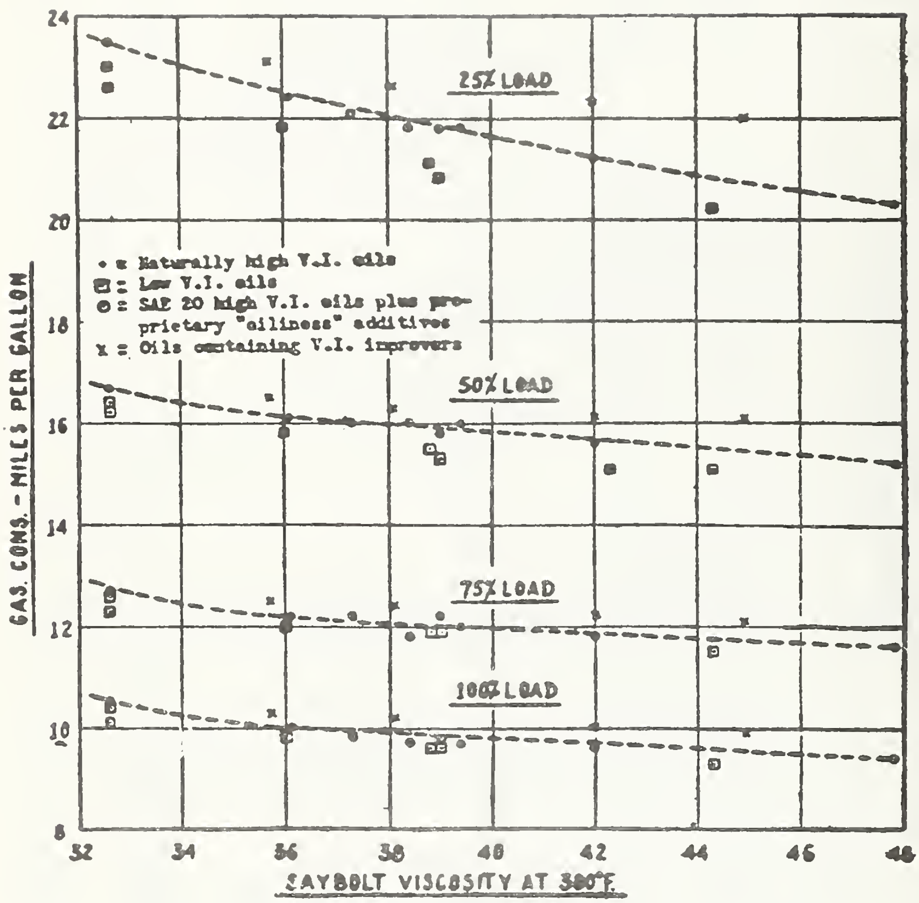
Source: From Reference 26.

FIGURE 3-1. AVERAGE FUEL CONSUMPTION VERSUS MOTOR-OIL VISCOSITY



Source: From Reference 26.

FIGURE 3-2. AVERAGE FUEL CONSUMPTION VERSUS MOTOR-OIL VISCOSITY AT 210°F



Source: From Reference 26.

FIGURE 3-3. AVERAGE FUEL CONSUMPTION VERSUS MOTOR-OIL VISCOSITY AT 300°F

summarized in Table 3-1. The use of a straight SAE 5W motor oil provided an increase of 3 to 6 percent in miles per gallon compared to a typical SAE 20 or 20W grade while the use of typical SAE 50 grade caused a decrease of 5 to 7 percent in miles per gallon. On the average, a change by one SAE viscosity grade produced a change of around 2 or 3 percent in miles per gallon.[26]

In the same year Miller and Hartman also showed that fuel economy could be improved by reducing the 98.9°C oil viscosity. Figure 3-4 shows the data they obtained in a laboratory engine running at road load. For each 10 SU reduction in 98.9°C kinematic viscosity it is possible to obtain a 2 percent increase in fuel economy.[27]

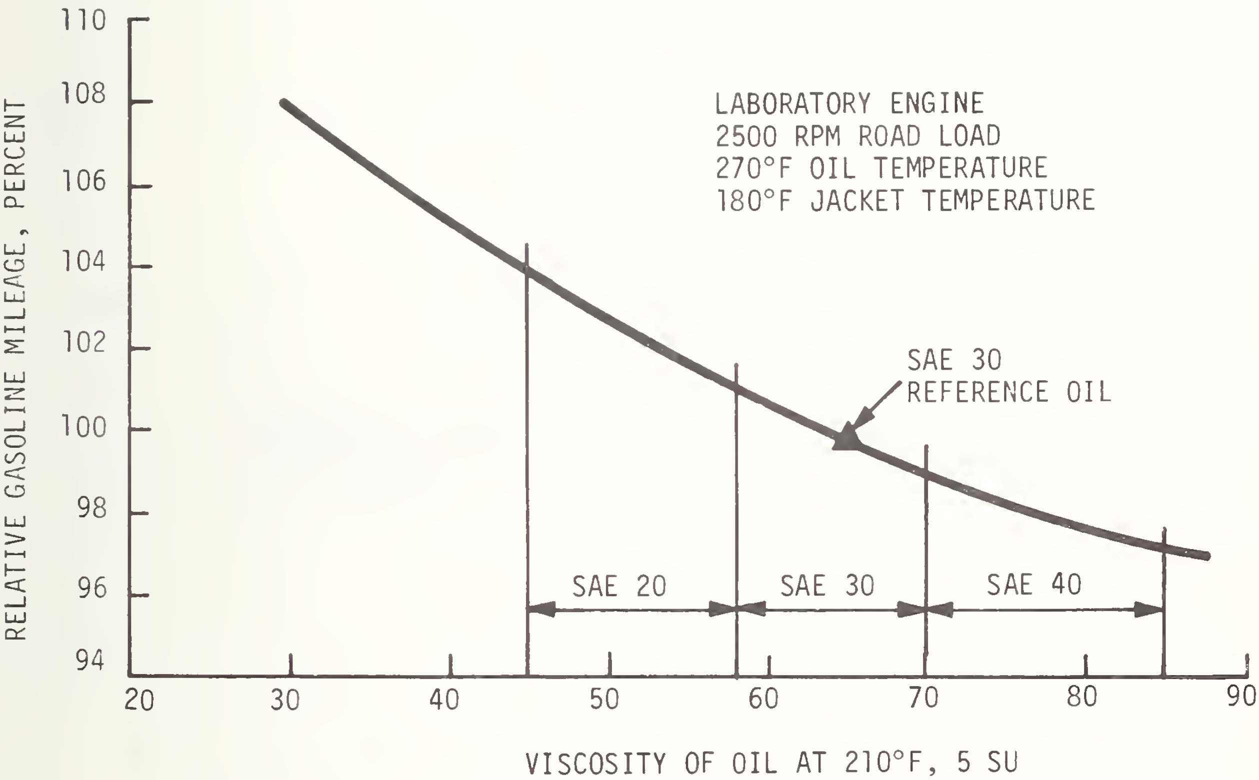
Again in 1954 More, Kent, Lakin and Mattson presented a report about the influence of viscosity on engine friction and fuel economy for both single and multigrade oils. Typical results are shown in Figures 3-5, 3-6, 3-7 and 3-8. Their conclusions were: considerable gasoline economies can be obtained with multigrade lubricants; savings from 5 to 10 percent would be expected for a typical passenger car driving at moderate ambient temperatures; for very short trip driving, or at low ambient temperatures, larger savings would be achieved; these gasoline savings appear to have a minimum value of about 3 percent even for very long trips with fully warmed up engines.[28] Single and multigrade oils of the same viscosity (determined according to ASTM D-445 method) show, on a running engine, different viscosity values. As a matter of fact, because of the well-known phenomenon of temporary viscosity loss, multigraded oils show viscosity values lower than single grade ones. In the same period, Towle demonstrated the possibility of reaching a fuel economy by as much as 5 percent by changing engine oil viscosity grade for SAE 30 to SAE 10W.[29]

In 1975 Chamberlin and Sheahan presented at an SAE Congress a report on preliminary engine dynamometer and road test data developed to determined automotive fuel saving through selected lubricants (engine and power train oils, mineral and synthetic). A vehicle track test has demonstrated improved gasoline engine

TABLE 3-1. TYPICAL FUEL-CONSUMPTION RATIOS AS RELATED TO OIL VISCOSITY GRADE

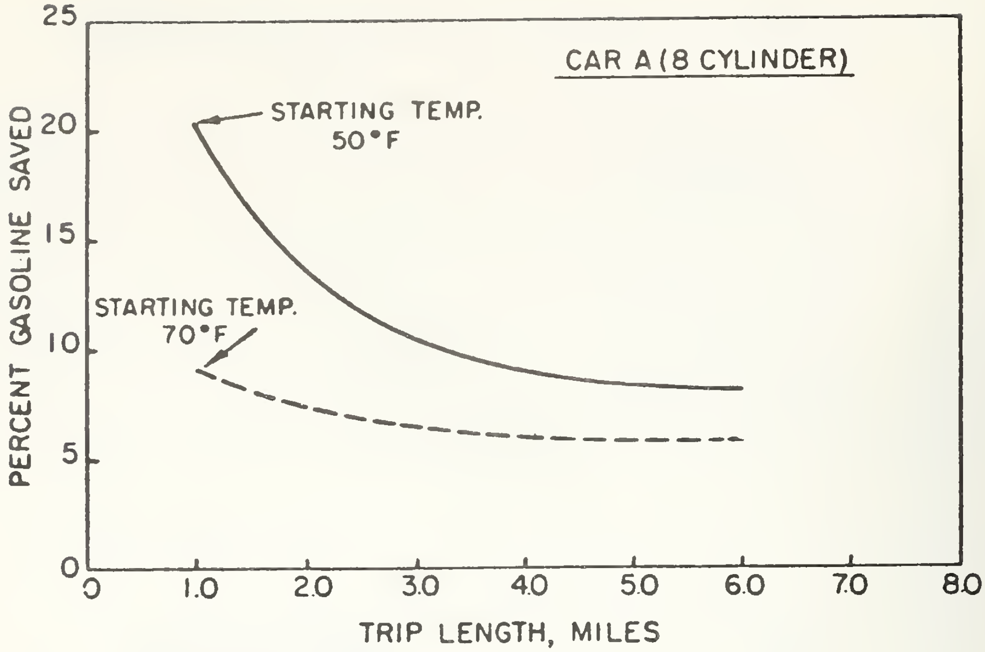
SAE Viscosity Grade	Gasoline Consumption Ratio
SAE 5W	1.03 to 1.06
SAE 10W	1.01 to 1.03
SAE 20-20W	1.00
SAE 30	0.96 to 0.98
SAE 50	0.93 to 0.95

Source: From Reference 26.



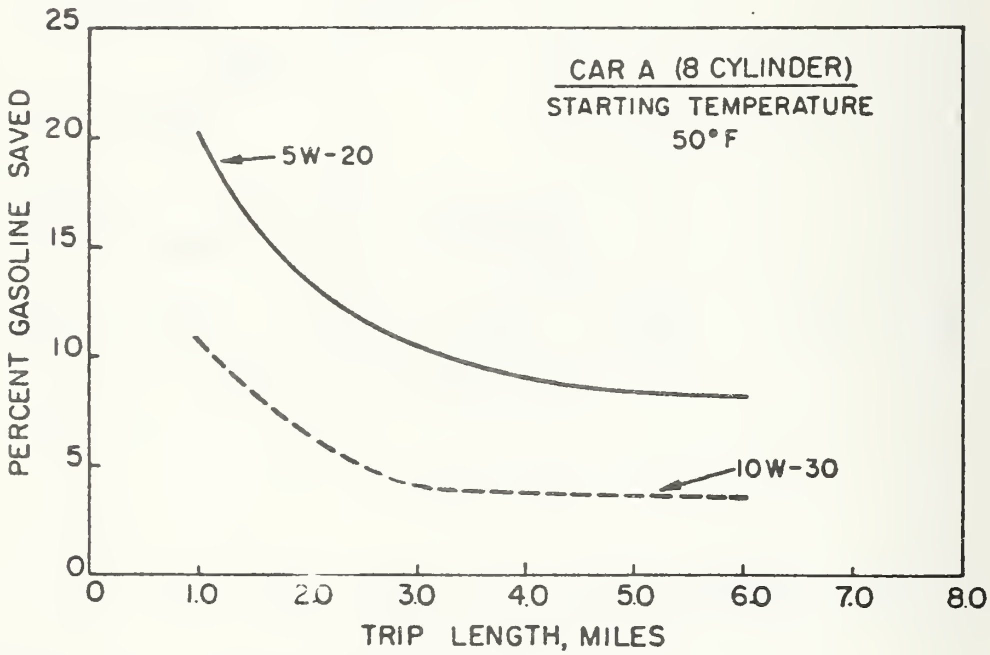
Source: From Reference 27.

FIGURE 3-4. EFFECT OF LUBRICATING OIL VISCOSITY ON GASOLINE MILEAGE



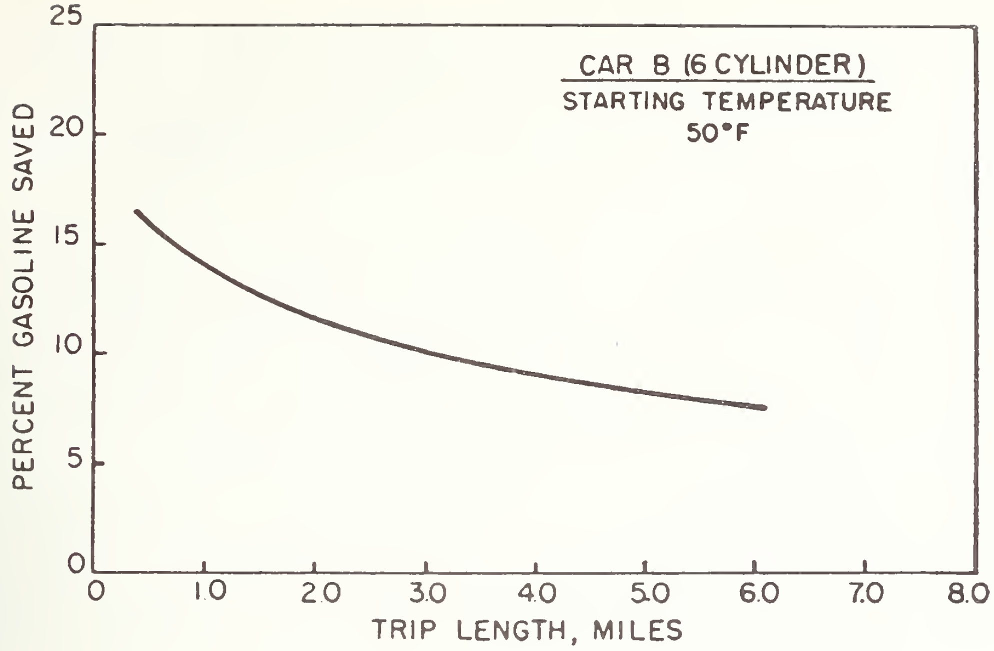
Source: From Reference 28.

FIGURE 3-5. EFFECT OF MULTI-GRADE LUBRICANT ON FUEL ECONOMY



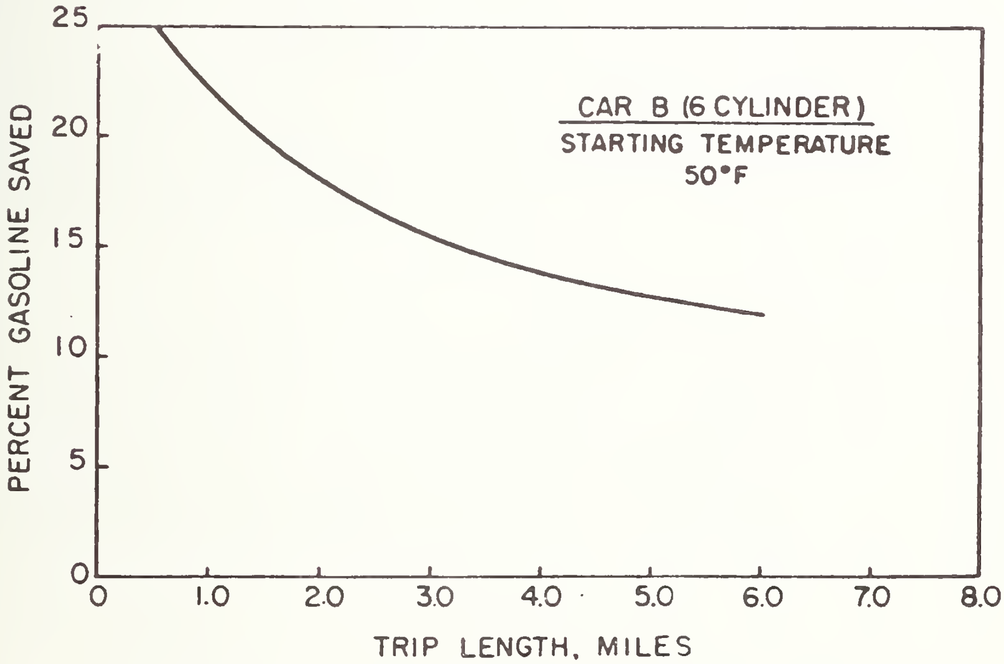
Source: From Reference 28.

FIGURE 3-6. EFFECT OF MULTI-GRADE LUBRICANT ON FUEL ECONOMY



Source: From Reference 28.

FIGURE 3-7. EFFECT OF MULTI-GRADE LUBRICANT ON FUEL ECONOMY



Source: From Reference 28.

FIGURE 3-8. EFFECT OF MULTI-GRADE LUBRICANT ON FUEL ECONOMY

fuel economy of 0.5 to 2.7 percent (Tables 3-2 and 3-3). Significant economy improvements (2.3 percent) for SAE 10W 40 oils over an SAE 40 were found in steady state engine dynamometer fuel consumption tests.[30]

The combined effect of engine oil and power train lubricant viscosity on fuel economy was investigated by Davidson and Haviland in the same year. They found that using low viscosity lubricants instead of high viscosity ones improved fuel economy by as much as 5 percent, depending on the differences in lubricant viscosity and type of driving (Figures 3-9, 3-10 and 3-11). For the cold-start driving cycles, the low viscosity lubricants gave a 5 percent greater fuel economy than the high viscosity lubricants (Figure 3-12).[31] In similar tests, Sheahan and Roming, in 1975, showed that low viscosity engine oils and gear oils combined could achieve a 3 percent improvement in fuel economy for four-mile trips starting with a cold engine. The improvement diminished as the trips lengthend.[32]

Slightly different conclusions were drawn in 1977 by Ciccarone from some motoring tests on some European engines with different engine oils and at different temperature. He concluded that not so important fuel consumption advantages seem to be attainable by using low viscosity oils: the maximum possible fuel consumption advantages do not exceed, in the examined case, one per cent (Figure 3-13).[33]

In 1978 Farnsworth, Bachman and Overton presented the results obtained with two groups of 10 city buses, each in regular service during the winter season. Statistical data analysis indicates a "most probable" improvement in fuel mileage of 2.7 percent using an SAE 15W40 oil compared to an SAE 40 one (Figures 3-14 and 3-15).[34]

3.3 FUEL ECONOMY WITH SYNTHETIC OIL

At the beginning of 1975 Richman and Keller showed that it is possible to obtain definite fuel economy advantages using a

TABLE 3-2. EFFECT OF ENGINE AND DRIVELINE LUBRICANTS ON FUEL ECONOMY

Lubricant Set	Time	Mean Fuel Economy (mpg)	Improvement Over Baseline (mpg)	Improvement Over Baseline %
1 (Baseline)	A.M.	12.90		
	P.M.	13.14		
2 (Engine Oil 1/ Baseline ATF/ Baseline Gear Oil)	A.M.	13.18	0.28	2.2
	P.M.	13.29	0.15	1.1
3 (Engine Oil J/ ATF TD/Gear Oil GJ)	A.M.	13.07	0.17	1.3
	P.M.	13.20	0.06	0.5

To Average Ambient Conditions During Test (30.76 in Hg pressure. 62.6°F temperature and 46 grains/lb dry air humidity) from Equation 21.

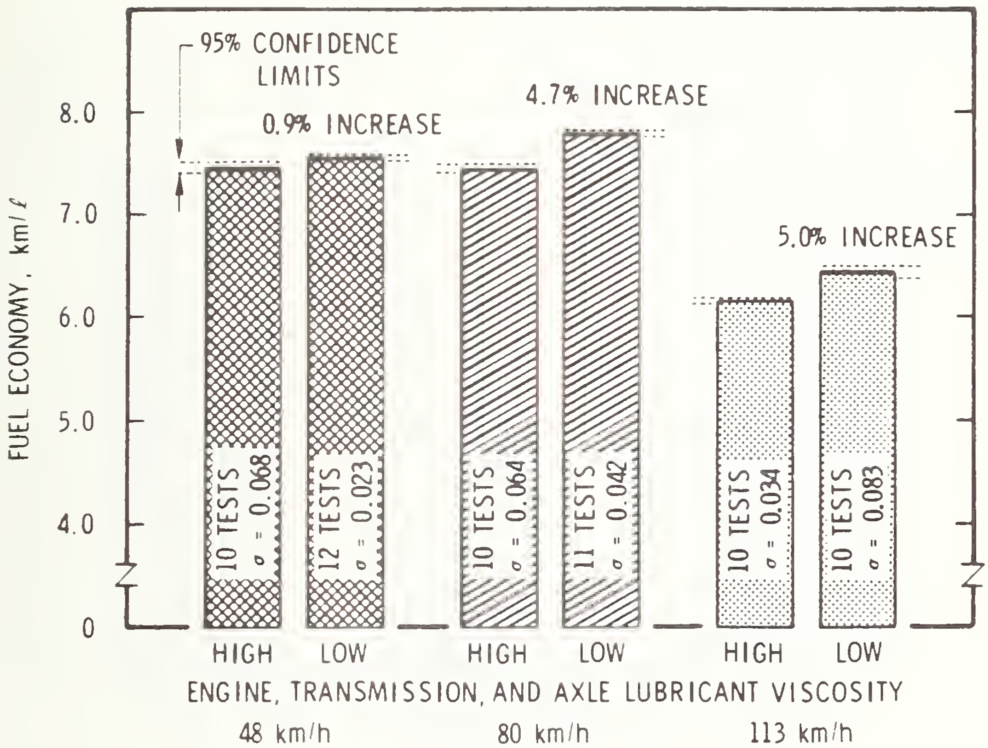
Source: From Reference 30.

TABLE 3-3. EFFECT OF ENGINE AND DRIVELINE LUBRICANTS ON FUEL ECONOMY

Lubricant Set	Corrected* Fuel Economy (mpg)	% Improvement Over Lubricant Set		
		1	2	3
1 (Baseline)	13.02			
2 (Engine Oil 1/ Baseline ATF/ Baseline Gear Oil)	13.24	1.7		0.8
3 (Engine Oil J/ ATF TD/Gear Oil GJ)	13.13	0.8		
4 (Engine Oil J/ Baseline ATF/ Gear Oil GJ)	13.37	2.7	1.0	1.8

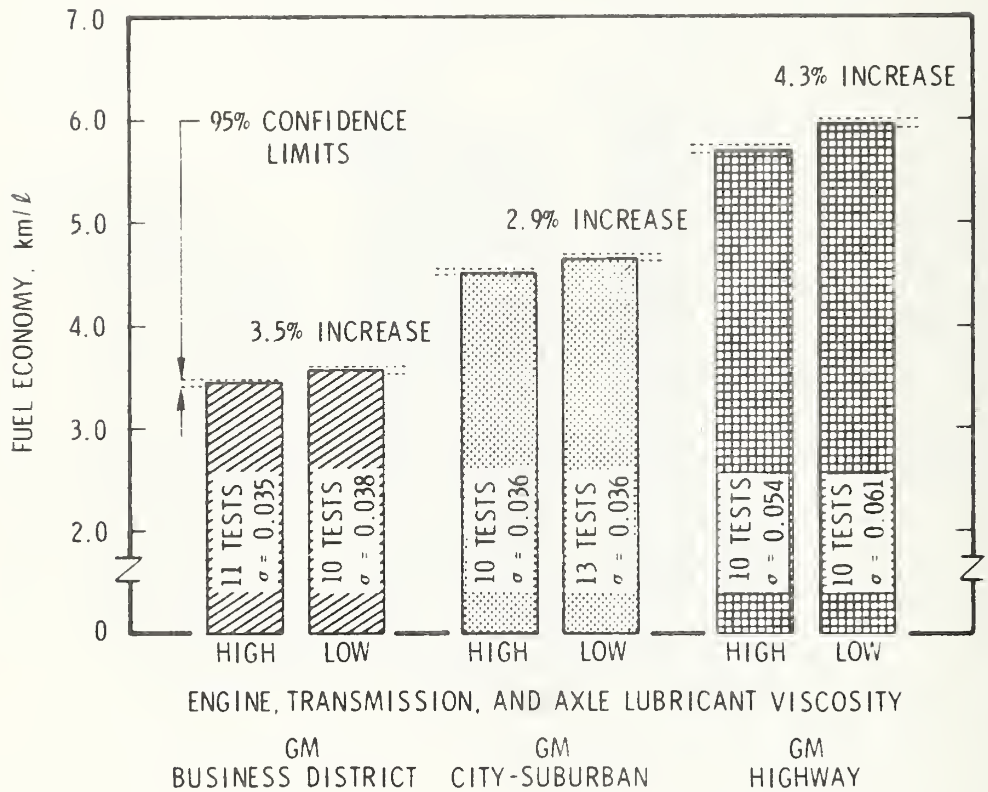
*To 30.76 in Hg pressure, 52.6°F temperature and 46 grains/lb dry air humidity from Equation 21.

Source: From Reference 30.



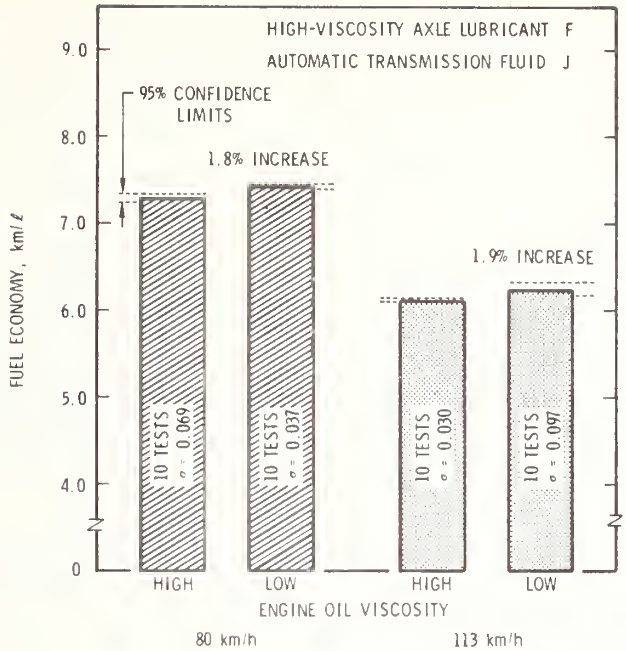
Source: From Reference 31.

FIGURE 3-9. FUEL ECONOMY IN WARMED-UP CONSTANT SPEED TESTS - EXPERIMENTAL LUBRICANTS



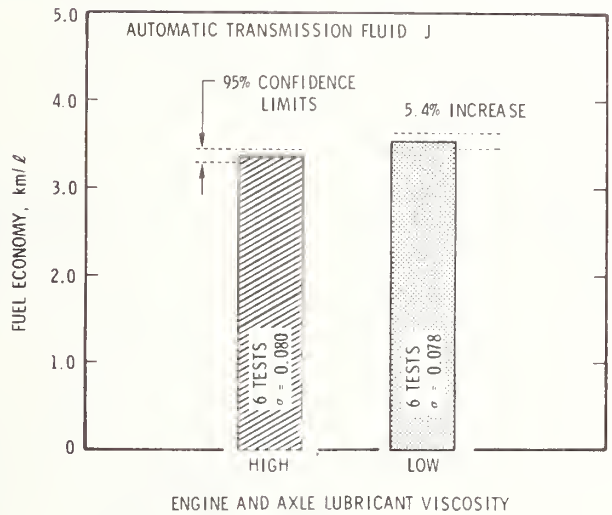
Source: From Reference 31.

FIGURE 3-10. FUEL ECONOMY IN WARMED-UP CONSTANT SPEED TESTS - EXPERIMENTAL LUBRICANTS



Source: From Reference 31.

FIGURE 3-11. FUEL ECONOMY IN WARMED-UP CONSTANT SPEED TESTS - COMMERCIAL ENGINE OILS



Source: From Reference 31.

FIGURE 3-12. FUEL ECONOMY IN COLD-START GM CITY-SUBURBAN CYCLE TESTS-COMMERCIAL LUBRICANTS

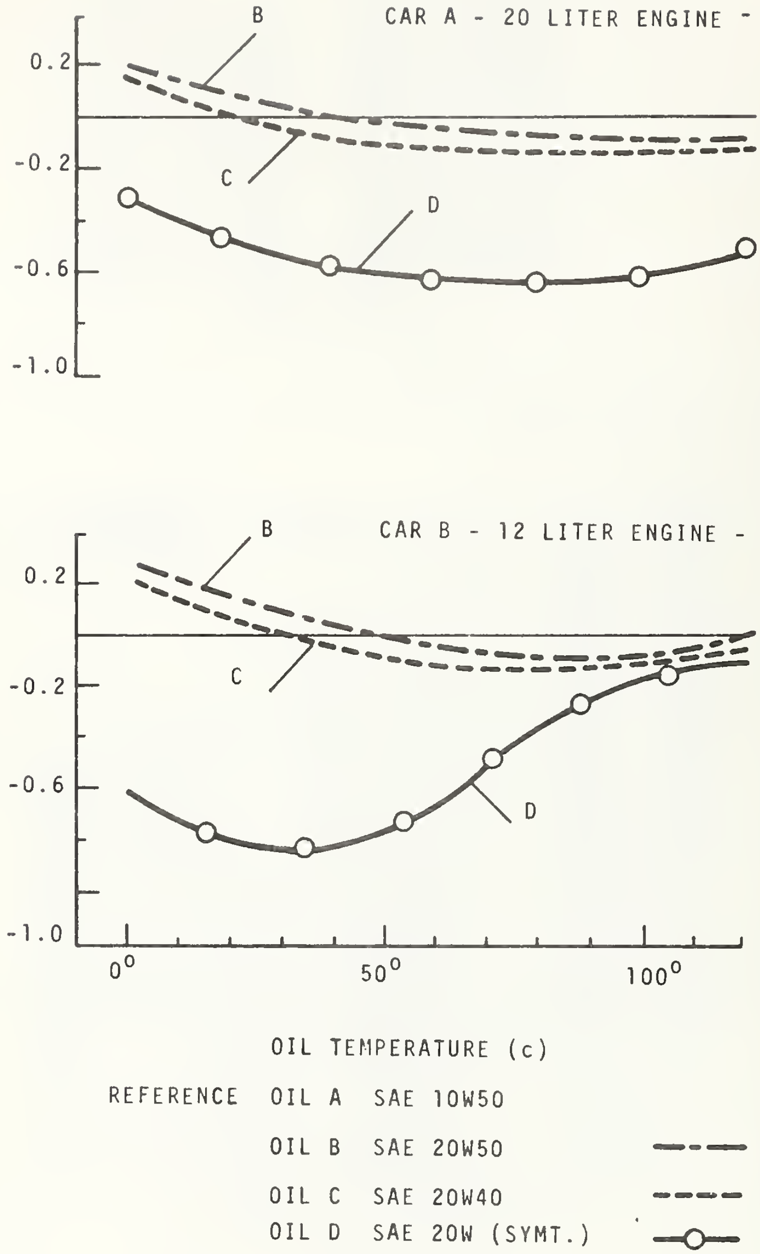
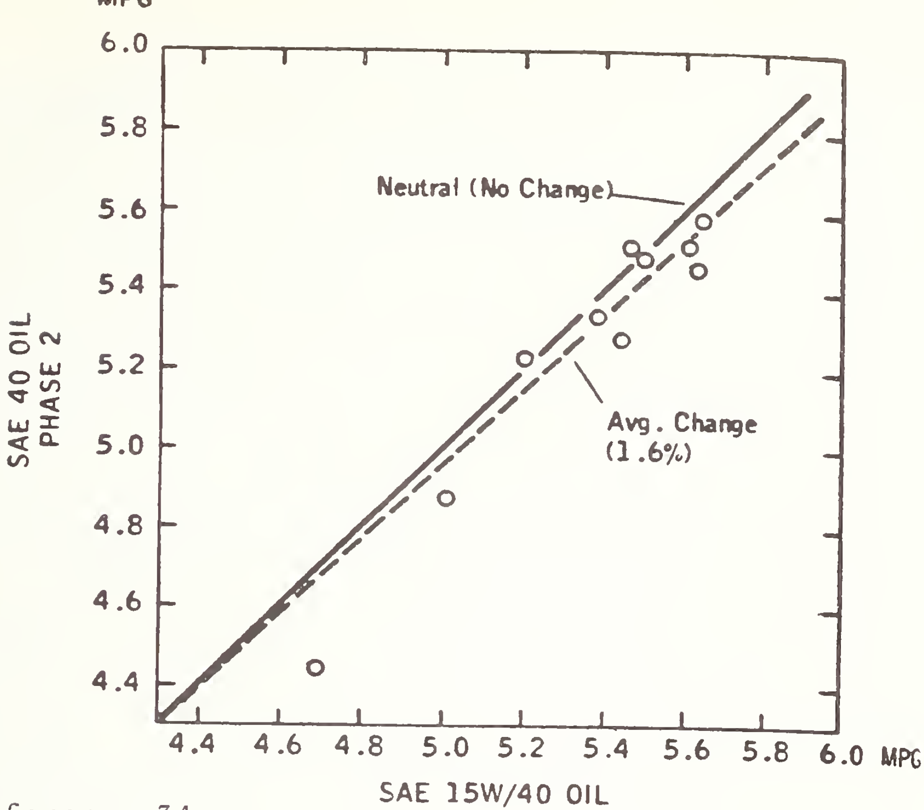
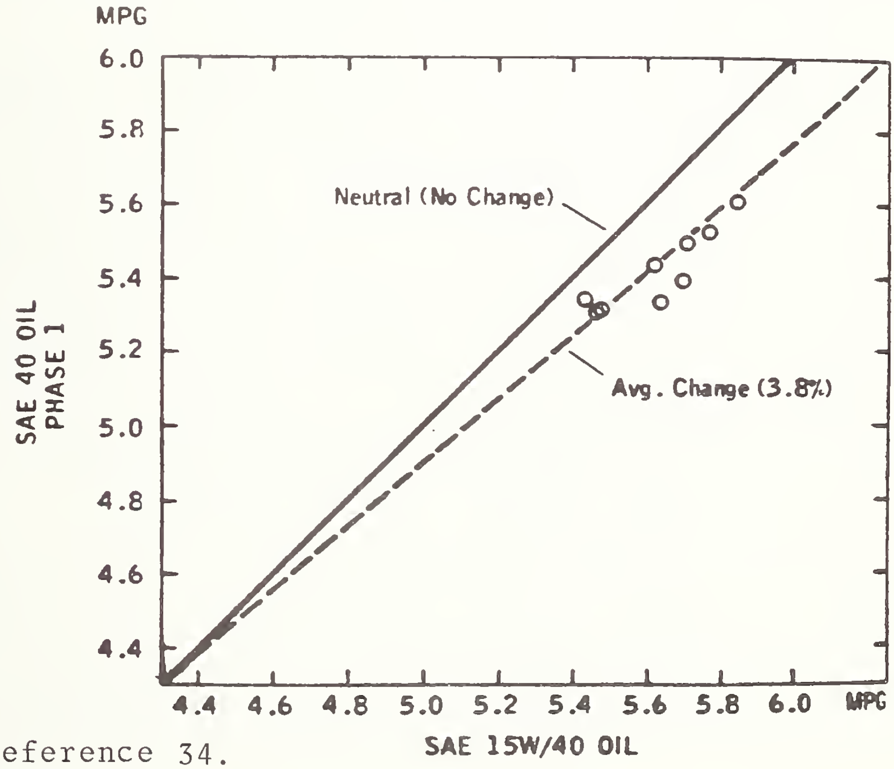


FIGURE 3-13. INFLUENCE OF OIL CHARACTERISTICS ON FUEL CONSUMPTION OVER THE EUROPEAN CYCLE



Source: From Reference 34.

FIGURE 3-14. AVERAGE BUS FUEL ECONOMY-BUS GROUP I (10 UNITS)



Source: From Reference 34.

FIGURE 3-15. AVERAGE BUS FUEL ECONOMY-BUS GROUP II (9 UNITS)

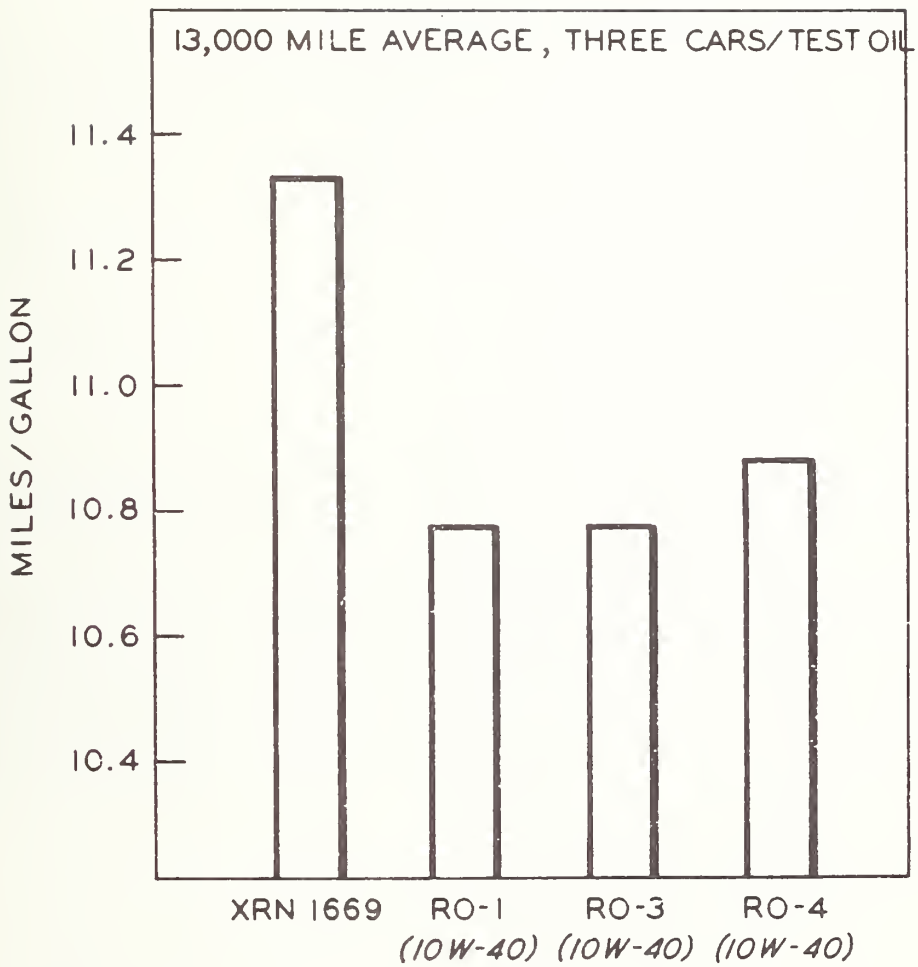
special type of low viscosity synthetic lubricant (SAE grade 5W20) without the problems experienced with low viscosity (SAE grade 10W40) mineral oil based products (excessive oil consumption and wear). Field and chassis dynamometer tests (typical results are reported in Figure 3-16 and Table 3-4) proved an average improvement in fuel economy ranging from 3 to 6.6 percent in comparison with mineral engine oil.[35] In the same year Boahringen presented the results of a 50,000 mile test conducted with cars driven over public roads. The cars, whose engines were lubricated with synthetic oil, used 172 gallons of fuel less than the cars equipped with mineral oil of equivalent viscosity grade. This represents a 3.7 percent savings.[36] Not in agreement with the above oponions were the conclusions of Rodgers and Kabel presented in the middle of 1975. As a matter of fact, (Table 3-5), they came to the conclusion that the use of synthetic and mineral oil of the same SAE grade brings equivalent fuel consumption results.[37]

In 1977 Krulish, Lowther and Miller presented the results (Figures 3-17 and 3-18) of a sequence of tests carried out under four different conditions: the European ECE 12 emission test cycle under both cold and hot conditions, a steady 20 Km/hr and a steady 120 Km/hr. In comparison with SAE grade 10W40, 10W50 and 20W50 mineral oils, the use of a special type of synthetic oil (5W20) produced an improvement in fuel economy ranging from 3.5 to 6.3 percent, according to the different testing conditions. In the same reports, the results obtained by the authors were summarized in a table (Table 3-6) together with the results obtained by other people and already published at that time.

Finally, calculations using the above data and based on short trip service (10 Km) involving a cold (ambient) start with 40 percent of highway driving show that the above synthetic lubricant provides an average improvement of over 5 percent. This is an important point because it is a well recognized fact that most passenger car trips are approximately of this length or less.[38]

3.4 FUEL ECONOMY WITH COLLOIDAL SUSPENSIONS IN MINERAL OIL

In 1975 Risdon and Gresty published detailed results of



Source: From Reference 35.

FIGURE 3-16. FUEL CONSUMPTION, CAR TEST D

TABLE 3-4. FUEL ECONOMY DATA CALCULATED FROM CVS EXHAUST EMISSION MEASUREMENTS (CAR TEST D)

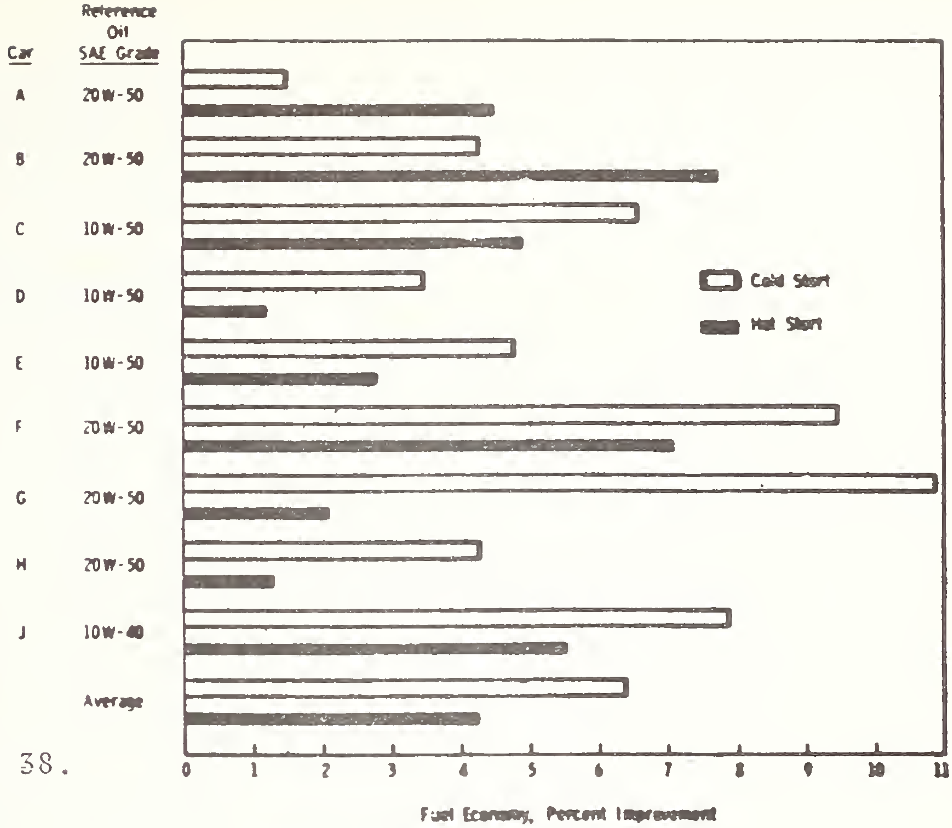
Test Vehicle	Vehicle Mileage	% Improvement in Fuel Economy for XRN 1669 over Mineral RO-1	
		LA-4 Driving Cycle	HWFET Dr. Cycle
1974 360 CID V8	8,000	5	3
1974 2.3 Liter OHC 4	21,000	9	3
1971 400 CID V8	36,000	6	4
1971 400 CID V8	42,000	7	1
1968 318 CID V8	51,000	6	4
Average		6.6	3.0

Source: From Reference 35.

TABLE 3-5. OVERALL FUEL AND ENGINE OIL ECONOMIES

Vehicle Number:	1	2	3	4	5
Engine Oil :	A	A	B	C	D
Change Interval, km:	12 000	32 000	32 000	32 000	32 000
Average Fuel Economy, km/l	5.85	5.96	5.73	5.70	5.62
Average Oil Economy, km/l	2740	3200	2170	3100	2800

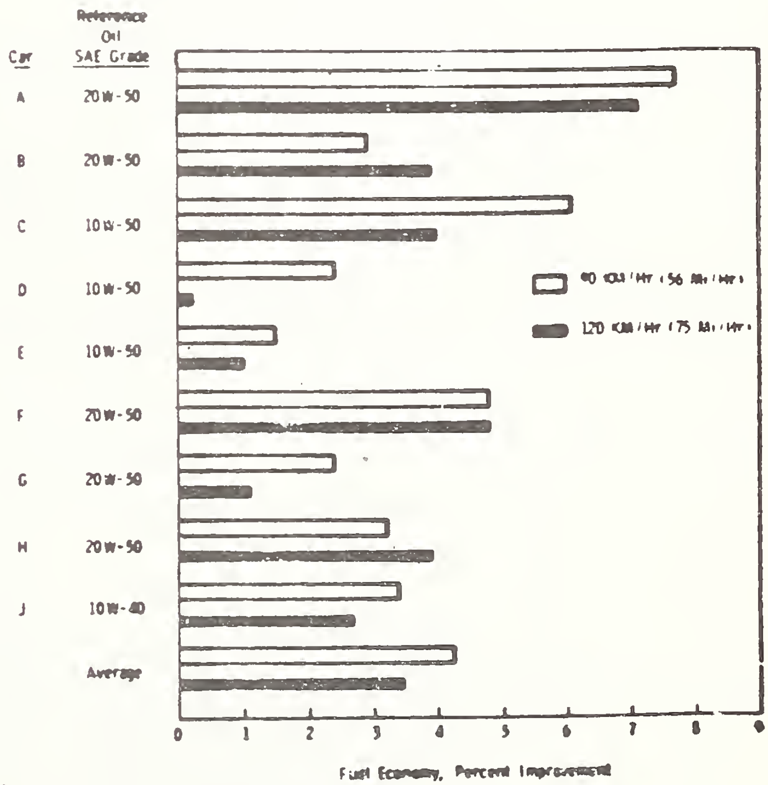
Source: From Reference 37.



Source:

From Reference 38.

FIGURE 3-17. ECE 15 FUEL ECONOMY TEST RESULTS



Source: From Reference 38.

FIGURE 3-18. CONSTANT SPEED FUEL ECONOMY TEST RESULTS

TABLE 3-6. FUEL ECONOMY TESTING

Test Procedure	No. of Direct Comparisons	Vehicle Tested	Percent Improvement(1) Over Reference Oil
EPA City Cycle	13	U.S. Cars	4
EPA Highway Cycle	13	U.S. Cars	2
EPA City Cycle	10	European Cars	6
EPA City Cycle (Hot Start)	10	European Cars	4
Various Chassis Rolls Cycles	7	U.S. and European Cars	4
Road Tests	6	U.S. Cars	4
Road Tests	7	U.S. Consumer Usage	6
Road Tests	8	European Cars	4
ECE 15 Cycle (3)	9	European Cars	4
ECE 15 Cycle (Cold Start)(3)	9	European Cars	6
90 Km/Hr(3)	9	European Cars	4
120 Km/Hr(3)	9	European Cars	3
Total	110(2)	Weighted Average	4.2

(1) Reference Oil Viscosity in most cases was SAE 10w-40 for U.S. cars and SAE 10w-50 or SAE 20w-50 for European cars.
(2) Representing over 600 data points.
(3) Independent Testing Authority.

Source: From Reference 38.

dynamometer, track, fleet and leased car tests sponsored or conducted during the period 1963-1974 by an important American manufacturer of solid additives for lubricant. Results may be summarized as follows:

- 1963 dynamometer tests

These tests were conducted using two baseline engine oils with and without 1 percent weight MoS_2. One oil was a premium detergent SAE 20 oil and the tests were conducted using a 1961 model 394 C.I.D. V-8 engine; the second engine oil was a non-detergent SAE 20 oil and the tests were conducted using a 1960 model 283 C.I.D. V-8 engine. The results of the tests, given in Table 3-7, indicated an improvement of 0.5 - 2.3 percent in Brake Specific Fuel Consumption (BSFC) at both full load and road load conditions for the oil containing MoS_2.

- 1964 dynamometer tests

This series of evaluations was conducted with a 1964 model 260 C.I.D. V-8 engine and used a premium detergent SAE 20 baseline oil. This time 3 percent weight and 7 percent weight MoS_2 engine oil treatments and a proprietary dispersion which gave a 3 percent weight MoS_2 concentration in the baseline oil were evaluated. The BSFC data (Table 3-8) showed an average improvement ranging from 2.5 to 5.6 percent.

- 1969-1971 dynamometer and track tests

An extensive series of comparative dynamometer and track tests was conducted using a MoS_2 dispersion technology developed in 1964-68, with MoS_2 treatments of 0.2 - 3 percent weight. Test results are reported in Tables 3-9, 3-10, 3-11 and 3-12.

- 1972-1974 fleet tests

All the data previously obtained suggested the need to develop fuel consumption data under the less rigorously controlled conditions of highway use. Two fleet test programs were carried out with a fleet of 23 gasoline powered school buses and the second using 13 company personnel operated leased cars. The results, summarized in Tables 3-13 and 3-14, show an average

TABLE 3-7. PERCENTAGE CHANGE IN BSFC AT FULL AND ROAD LOADS

Engine RPM	1961 V-8 394 CID SAE 26 Premium Oil (SD) Percentage bsfc lb/bp/hr		1960 V-8 283 CID SAE 20 Non Detergent Oil Percentage bsfc lb/bp/hr	
	Full Load	Road Load	Full Load	Road Load
800	+1.2		-1.7	-
1200	+1.3	0	-3.4	-0.8
1600	+ .4	-4.4	-1.7	-4.9
2000	+ .2	-1.3	+0.2	-0.5
2400	+ .4	-1.5	+2.0	-1.3
2800	-1.9	-2.7	+3.7	-4.8
3200	-1.5	-3.0	-2.4	-2.3
3600	-2.5	-2.9	-2.5	-1.5
4000	-1.9	-3.3	-3.4	-2.2
Weighted Avg Change in bsfc	-0.5	-2.3	-1.1	-2.3

Source: From Reference 39.

TABLE 3-8. PERCENTAGE CHANGE IN BSFC AT FULL AND ROAD LOADS

1964 V-8 260 CID Engine

Using MoS_2 in SAE 20 Premium Oil (SD)

Engine RPM	3% MoS_2 Powder Percentage BSFC lb/hp/hr		7% MoS_2 Powder Percentage BSFC lb/hp/hr		3% Comm'l Dispersion Percentage BSFC lb/hp/hr	
	Full Load	Road Load	Full Load	Road Load	Full Load	Road Load
800	1.8		-1.6		-	-
1200	0.6		-1.0	+0.8	-0.8	+0.8
1600	1.8	1.0	-1.4	1.0	-1.8	-1.9
2000	2.3	3.2	2.5	1.3	-3.6	-2.7
2400	7.5	1.9	8.1	2.8	-7.5	-4.8
2800	1.8	-3.2	6.8	-3.9	-7.4	-5.9
3200	-4.7	-5.2	5.3	-6.1	-6.5	-7.2
3600	1.6	-4.3	-5.5	7.6	-5.7	-9.4
4000	-5.6	-4.1	-10.4	-7.7	-7.2	-11.5
4400	8.7	-	-12.8		-12.0	
Weighted Avg. Change in bsfc	3.7	-2.5	-5.6	-2.9	-5.3	-4.2

Source: From Reference 39.

TABLE 3.9. 1968 OLDSMOBILE V-8 350 CID DYNAMOMETER TESTS ON MOTOR OILS CONTAINING MoS_2 - PERCENT CHANGE WITH MoS_2

Baseline MS SAE 20-20W Oil			0.2% JP-2 MoS_2		1% JP-2 MoS_2		3% JP-2 MoS_2	
rpm	hp	% Change in Fuel Consumption (bsfc) Rvhp/hr	% Change in HP	% Change in Fuel Consumption	% Change in HP	% Change in Fuel Consumption	% Change in HP	% Change in Fuel Consumption
2000	66.4	1.027	6.9	9.2	3.6	1.6	2.9	-4.5
2400	78.8	1.088	0.8	8.1	2.7	-15.3	3.7	-17.9
2800	94.9	0.966	1.9	8.4	7.1	-5.4	5.9	-5.0
3000	114.6	0.878	3.5	0.3	2.9	0.8	3.9	2.7
3200	148.7	0.788	-4.6	-2.8	4.2	-7.1	1.5	-2.2
3600	176.5	0.680	-2.6	2.7	1.0	-3.4	0.3	-2.9
4000	227.2	0.552	-3.8	3.5	5.7	-8.9	3.6	-7.1
4200	249.3	0.486	3.8	4.2	1.5	-3.3	1.2	-4.3
4600	250.5	0.485	3.9	5.6	3.8	-5.8	0	-3.3
5000	252.3	0.468	4.9	-3.6	3.8	-4.7	4.8	-5.8
Weighted % Average Change Throught Speed Range			1.0	-3.9	3.4	5.8	2.4	-5.4
Weighted % Average Change From 3000 to 4800 rpm			1.0	4.0	3.3	-5.7	2.0	-4.2

Source: From Reference 39.

TABLE 3-10. CHEVROLET 350 CID V-8 ENGINE - FUEL CONSUMPTION AT TEST STAND

SDQ 20-20W Baseline Oil	Baseline Oil +10% PIB	Baseline Oil +10% PIB +0.5% MoS_2†	Δ	% Change
535.9	533.8 510.5	481.9	- 2.0 -28.6	-0.38 -5.62

oHigh energy operation with inertia weight at 5500 lb and shifts at 4500 rpm
†Per 120 hour segment
†JP-2 MoS_2(Climax Suspension)

SDQ = SD quality

PIB = Polyisobutylene-based additive

Source: From Reference 39.

TABLE 3-11. FUEL CONSUMPTION - TEST TRACK

Car No*	SDQ 20-20W Baseline Oil	0.5%	1%	3%	Δ	% Change
407	670.8	-	633.5	-	-37.3	-5.56
409	637.8	-	589.0	-	-48.8	-7.65
413	679.5	-	649.1	-	-30.4	-4.47
415	637.6	-	-	608.3	-29.3	-4.59
416	659.5	-	-	632.3	-27.2	-4.12
507	599.4	597.4	-	-	- 2.0	-0.34
434†	-	-	-	647.7	-	-
-	646.0	-	-	-	+ 1.7	+0.26
-	-	-	-	640.0	- 6.0	-0.93

*All cars were 1969 models having 429 CID engines.

†Test sequence was changed. Instead of using baseline oil first and then the MoS_2 containing oil (the procedure for the previous five tests), the MoS_2 containing oil was run first followed by baseline oil, a repeat run was then made using the MoS_2 containing oil.

SDQ = SD quality

Source: From Reference 39.

TABLE 3-12. SPECIFIC FUEL CONSUMPTION DURING 400 HOURS TEST RUNNING 1498cc 4-CYLINDER ENGINE

Days Run	Max. Torque s.f.c.(lb/bhp:h)	Max. Power s.f.c.(lb/bhp:h)	Lubricant	S.F.C. Improvement From Baseline Test	
2	0.683	0.837			
4	0.667	0.798			
6	0.661	0.780	Baseline SD		
8	0.658	0.773	Quality Iuk		
10	0.662	0.778	20-20W		
12	0.659	0.773		Max. Torque	Max. Power
14	0.662	0.775			
16	0.656	0.773			
18	0.652	0.759			
20	0.654	0.753	Baseline		
22	0.649	0.749			
24	0.648	0.750	+1% MoS_2		
26	0.652	0.747			
28	0.651	0.748		1.7%	3.5%
30	0.650	0.755			
32	0.654	0.757	Baseline		
34	0.648	0.753			
36	0.647	0.752	+3% MoS_2		
38	0.650	0.755			
40	0.647	0.750			
42	0.648	0.752		2.1%	3.0%
44	0.648	0.753			
46	0.649	0.754	Baseline		
48	0.650	0.752	20-20W		
50	0.648	0.750			
52	0.652	0.754			
54	0.653	0.755			
56	0.655	0.760		1.0%	1.9%

Source: From Reference 39.

TABLE 3-13. SCHOOL BUS FLEET TEST WITH A ONE PERCENT MoS_2 SUSPENSION

Comparison of Fuel Consumption
MoS_2 Group Versus Control Group*

Month	1971-72 (Before MoS_2)	1972-73 (After MoS_2)	Net % Change with MoS_2
October	+4.78	+13.19	8.41
November	+1.02	+7.21	6.19
December	+0.60	+8.39	7.79
January	+4.36	+4.94	0.58
February	+15.51	+0.66	-14.85
March	+3.76	+4.44	0.68
April	-2.81	+5.60	8.41
May	-2.37	+4.06	6.43
June	+10.18	+8.62	-1.56
Overall % Difference in mpg	+3.89	+6.35	2.46
With February Omitted	+2.44	+7.06	4.62

$$\frac{{}^{*}MoS_2 \text{ Average} \quad \text{Control Average}}{\text{Control Average}} \times 100$$

Note that (+) values represent lower fuel comsumption or better fuel economy.

Source: From Reference 39.

TABLE 3-14. COMPANY LEASE CAR FLEET TEST

Participant	Car Make	Engine Displacement CID (1)	Total Miles Accumulated	Miles Accumulated on MoS_2 Oil	% Improvement in Fuel Economy With MoS_2	
					December 1973	June 1974 (a)
1	A	400 (6.6)	34,586	16,802	- 1.4	+ 1.7
2	A	350 (6.7)	36,477	13,583	+ 9.3	+ 7.6
3	A	350 (5.7)	13,428	2,335	+ 2.6	- 0.3
4	A	400 (6.6)	49,008	31,143	+ 8.5	+14.2
5	A	350 (5.7)	71,691	35,713	+ 2.0	+ 2.4
6	A	400 (6.6)	26,318	9,418	+ 6.1	-
7	A	350 (5.7)	36,274	21,812	- 4.8	-
8	B	400 (6.6)	39,260	10,467	0.0	- 0.8
9	B	400 (6.6)	73,802	48,004	+ 3.8	+ 9.5
10	C	455 (7.5)	38,247	16,451	+ 2.5	+ 6.5
11	C	455 (7.5)	34,145	14,475	- 0.2	- 3.6
12	D	455 (7.5)	18,362	4,335	+12.1	-
13	D	400 (6.6)	42,085	18,215	- 2.6	+ 0.2
Average			39,514	18,673	+ 2.9	+ 3.7

(a) Includes after United States National Speed limit was reduced to 55 mph.

Source: From Reference 39.

improvement in fuel consumption of 4 to 6 percent for the buses and of 3.7 percent for leased cars.

All fuel consumption data presented above were analyzed statistically to determine the range of value at the 95 percent confidence level. The result obtained was an average improvement in fuel consumption of 4.4 percent due to a 1 percent weight MoS_2 treatment in the engine oil with a range of 2.3 - 6.4 percent.[39]

In the same year Bennington, Cole, Ghirla and Kennedy Smith evaluated the influence of stable colloid lubricant additives on vehicle fuel economy through modification of engine friction. The SAE J-1082 procedure was used to determined fuel consumption in tests conducted on a seven vehicle fleet; the change in fuel economy after one or more oil changes, using colloid lubricant additives for each vehicle in the test fleet, and the range of changes in fuel economy with respect to indivudual baseline fuel economy are reported respectively in Tables 3-15 and 3-16. In addition, an extended dynamometer test was conducted on the most promising colloid additive system; after 100 hours of tests at 55 mph (road-load), fuel consumption was reduced by approximately 2 percent.[40]

TABLE 3-15. CHANGE IN CORRECTED MILES PER GALLON. OIL R COMPARED TO OIL R PLUS COLLOID ADDITIVE IN SAE J1082 TEST CYCLES

Colloid Additive	Car No.	Test Miles	Increase/Decrease, MPG Urban	Suburban	Interstate
A	170	12000	-0.74	+0.22	-0.47
	170	18000	+0.56	-0.06	+0.10
A	221	12000	+0.33	+0.37	+0.43
	221	18000	+1.17	+0.99	+0.28
B	211	12000	+1.43	+0.89	+1.06
	211	18000	+0.79*	-0.62*	-0.64*
B	212	12000	+0.65	+0.34	+0.35
	212	18000	+0.64	+0.02	-0.31
C	167	12000	+1.03	-0.07	-0.28
	167	18000	+0.74	+0.15	-0.53
C	220	12000	-0.41	-1.11	+0.68
	220	18000	-0.04	-1.28	+0.26
B	148**	12000	+0.21	-0.01	0.00
	148**	18000	+0.23	+0.07	+0.27

*Burned exhaust valves. Data not valid

**Oil S and Oil S + Colloid Additive

Source: From Reference 40.

TABLE 3-16. FUEL ECONOMY CHANGE

Test Cycle	% Improvement in MPG	
	Minimum	Maximum
Urban	-0.3	22.4
Surburban	-1.9	8.2
Interstate (70 mpg)	-4.1	9.6

Source: From Reference 40.

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